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Subnormal glow discharge of ionized gases in presence of a longitudinal magnetic field

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Abastract : In subnormal glow region, the average tube current, voltage across the tube, residual current and oscillation parameters in the discharge of ionized gases have been measured for different initial tube currents and different pressures within the range of 500 mT to 1600 mT in presence of magnetic field varying from zero to 400 Gauss in air and hydrogen. The tube current, residual current and frequency of the current pulse gradually increase and voltage gradually decreases, and attains saturation with magnetic field. The effect can be interpreted theoretically by the normal Bessel function and the calculations agree well with the experiments. The reaction of residual current with magnetic field has also been recognized in their oscillations. The oscillation parameters of the current pulses have been examined in hydrogen.

Keywords : Subnormal glow, residual current, current pulses, electron temperature, oscillation parameters.

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1. Introduction

In the subnorml region, the current-voltage characteristic has a negative slope [1]. Ward [2] has shown that the experimentally observed negative resistance characteristics can be fitted in theoretical equations obtained by modifying Townsend's basic equation [3] in conjunction with the space-charge effect. Very little work has however, been done on the nature of current-voltage characteristics and the associated residual current in subnormal region [4]. Many workers [5–7] have investigated the nature of oscillations in the residual current in the subnormal region of the discharge in air. Though the analysis of the effect under a longitudinal magnetic field by Bickerton and Von Engel [8] based on some theoretical predictions and experimental observations are partially valid, some are equally valid in case of subnormal region. So, it may be examined whether the application of the magnetic field changes the radial distribution of electrons from the normal Bessel function. The efforts have been made in this paper to test the validity of Bickerton and Von Engel's predictions in case of subnormal region of discharge.

The variation of current, voltage in longitudinal magnetic field [9] can be extended to similar variation in theory of subnormal discharge.

In order to study the effect of a longitudinal magnetic field on the subnormal discharge and hence to bring out clearly the outstanding difference from the case when the magnetic field is transverse [7], we have studied the variation of current, voltage, residual current and oscillations parameters of current pulses in air and in hydrogen, in presence of a magnetic field at different presssures and average tube currents. An analysis of the experimental results enables us to obtain the axial variation of the distribution of the electrons with the applied magnetic field. We have also tried to provide a theoretical explanation of the observed variation. Our calculation enables one to understand the generation and loss mechanism of the electrons in a subnormal region of the discharge in longitudinal magnetic field.

2. Experimental procedure

Figure 1 shows the system used to measure the effect of magnetic field on the discharge and to study the parameters of oscillations of current pulses. The discharge tube is

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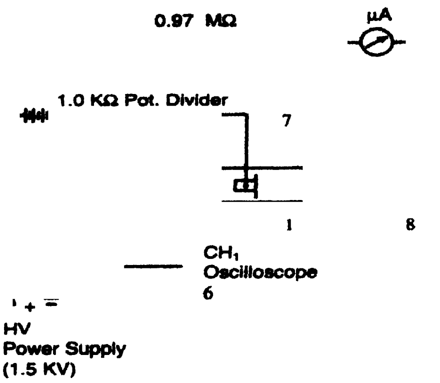


Figure 1. The apparatus : (1) Discharge tube, (2) Potential divider (1.0 KΩ) (3) Ballast resistor (0.97 MΩ), (4) A current meter, (5) High voltage unit, (6) Oscilloscope, (7) Voltmeter (VTVM), (8) Electromagnet (pole-pieces dia. 7.0 cm).

cylindrical pyrex glass of length 5.8 cm, radius 2.4 cm and fitted with two plane parallel copper electrodes of radius 2.0 cm at a distance of 1.80 cm. The tube is thoroughly cleaned and dried and placed within the pole pieces of an electromagnet so that the lines of force are parallel to the axis of the discharge tube. The pole pieces have the diameter of 7.0 cm which ensure that the magnetic field is uniform throughout the length of the tube. The electromagnet is energized by a stabilized power supply and the magnetic field has been measured by an accurately calibrated gaussmeter. The ballastic resistor 0.97 MΩ limited the average tube current and kept the HV unit within its current capacity. A 1 KΩ potential divider was connected between the discharge tube and earth to provide a signal to the oscilloscope (60 MHz digital storage, PM 3350, Phillips). Pure and dry air and spectroscopically pure and dry hydrogen were used as gas. The discharge tube was excited by a dc voltage from the high voltage unit with an insignificant ripple. A calibrated Mcleod gauge has been used to measure the pressure of the gas.

The experimental procedure and method of observation of the oscillation parameters of current pulses is the same as was used in a previous paper [10]. Both sweeps of the duel channel oscilloscope were made to overlap. The signal from 1 KΩ potential divider was connected to one of the channels (CH_1) and is seen as pulsation in the oscillogram.

The origin of the oscillations has its basis in the mechanism for the production of pulse, which involves [11] rapid ionization in the cathode region and the formation of the steep potential gradient relative to the positive column. When the velocity of the positive ions change as they cross the negative glow to enter the dark space, fluctuation in the discharge current occurs with a frequency corresponding to the total time involved in the process, which largely depends on the movement and collection of positive ions.

The origin of these pulsations is found to have shifted upward from the initial position set before the signal is applied. The shift indicates the presence of a residual current. It is measured by some workers [6,7] using the following relation,

Residual current (I_r) (without-magnetic field)

$$= \frac{\text{shift(cm)} \times \text{sensityvity(v/cm)}}{\text{resistance}}$$

and Residual current (IRH) (with-magnetic field)

$$= \frac{\text{shift due to magnetic field (cm)} \times \text{sensitivity} (V/\text{cm})}{\text{resistance}} .$$

Observations were made for initial tube currents 68, 100, 125 and 150 μA for air and 38, 100 μA for hydrogen. The magnetic field, supplied by a calibrated electromagnet was used and the pressure inside the discharge tube 0.10 to 1.5 torr. Keeping the different sets of pressures (*e.g.* 0.10, 0.15, 0.20, 0.40, 0.50, 0.60, 1.00, 1.25 and 1.50 torr) constant, the magnetic field was varied and the corresponding voltage across the discharge tube, average tube current, residual current and oscillations of current pulses have been measured for the values of magnetic field varying between 0 G to 400 G.

3. Results and discussion

The variation of the average tube current and voltage with magnetic field for different values of pressure have been plotted, for both air and hydrogen in Figures 2 and 3 respectively. It is observed that the current gradually

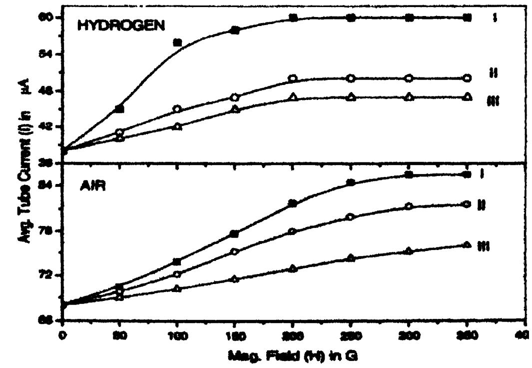


Figure 2. Variation of average tube current with magnetic field for air at pressure (*P*) : I : 0.15 torr; II : 0.15 torr; III : 0.20 torr. and for hydrogen at pressure (*P*) : I : 0.40 torr; II : 0 .50 torr; III : 0.60 torr.

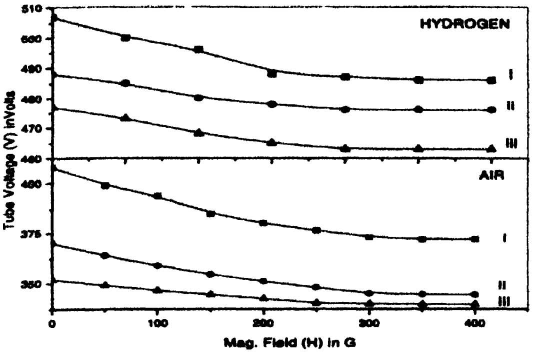


Figure 3. Variation of tube voltage with magnetic field for air at pressure (P) : I : 0.10 torr; II : 0.15 torr; III : 0.20 torr and for hydrogen at pressure (P) : I : 0.40 torr; II : 0.50 torr; III : 0.60 torr.

rises with the magnetic field and for the values of magnetic field greater than 300 Gauss in air and 200 Gauss for hydrogen, the current attains a saturation value. The fractional change is more marked in case of lower pressure, for the lower values of magnetic field. The corresponding voltage across the discharge tube decreases and for the values of magnetic field greater than 300 Gauss for air and 200 Gauss for hydrogen, the voltage assumes a constant value.

Figure 4 shows the variation of residual current (I_R) with magnetic field at fixed pressure of 0.50 torr for air and at fixed initial average tube current of 100 μA for hydrogen. It is observed that the residual current increases with the increase, specially of low values of magnetic field.

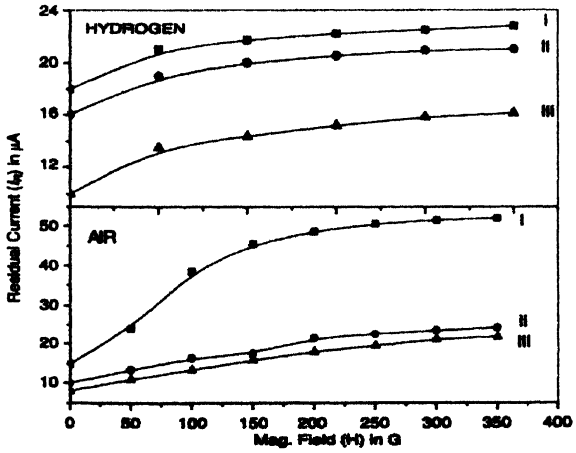
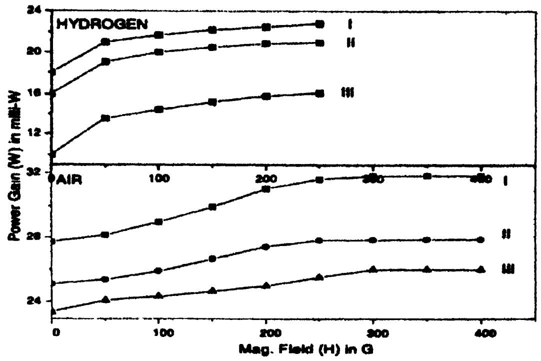


Figure 4. Variation of residual current with magnetic field for airat initial average tube current (I) : I : 150 μA; II : 125 μA; III : 100 μA; and for hydrogen at pressure (P) : I : 1.00 Torr; II : 1.25 torr; III : 1.50 torr.

Figure 5 shows the variation of power gain (W) with magnetic field for different values of pressure in air and hydrogen.



5. Variation of power gain (W) with magnetic field for air at pressure) : I : 0.10 torr; II: 0.15 torr; III : 0.20 torr ; and for hydrogen at pressure) : I : 0.40 torr; II : 0.50 torr; III : 0.60 torr.

A simple explanation of the observed results can be given. The average current density (j) [$j = \sigma E$] of the discharge is given by dc conductivity (σ) of the plasma and voltage drop per unit length (E), further

$$\sigma = ne^2/m\nu_c,$$

where n is number of electrons per unit volume and ν_c is the collision frequency for momentum transfer; then

$$j = ne^2\lambda_e E/mv_r,$$

λ_e is the mean free path of the electron and v_r is the random velocity. Hence,

$$j = ne^2\lambda_e E/\sqrt{(3mkT_e)},$$

where T_e is the electron temperature.

In the present experimental condition, the positive column extends from cathode to anode, l is taken to be the distance between the two electrodes. In this connection, Sen and Jana [9] have deduced an expression for the total current that may be represented by the total average tube current I in absence and I_H in presence of magnetic field. Then,

$$I = \frac{V_0 - (V_C + V_A)}{R + C} \quad (1)$$

$$\text{and } I_H = \frac{V_0 - (V_C + V_A)}{R + C_H}, \quad (2)$$

where V_0 is the supply voltage from HV unit, V_C and V_A are the cathode and anode fall, respectively. R is the series resistance (970 KΩ), C and C_H are defined as follows,

$$1/C = \frac{e^2 L}{Pl\sqrt{3mkT_e}} 2\pi \int_0^{R_w} nr\,dr \quad (3)$$

$$\frac{1}{C_H} = \frac{e^2 L}{Pl} \cdot 2\pi \int_0^{R_W} n_H r dr \tag{4}$$

where n, n_H and T_e, T_{eH} are electron density and electron temperature in absence and in presence of longitudinal magnetic field, respectively, l is the distance between the two electrodes, L is the mean free path of electron at 1 torr, R_w is the radius of the discharge tube. The values of V_C and V_A in case of air and hydrogen have been obtained from Brown [12] and from the experimental values of I and I_H. At different values of magnetic field, it is possible to calculate the values of C and C_H from eqs. (1) and (2) for the pressure 0.10 torr in air. Similar calculations have been performed for pressure 0.20 for air and 0.40, 0.50 torr for hydrogen and have been given in Figure 6.

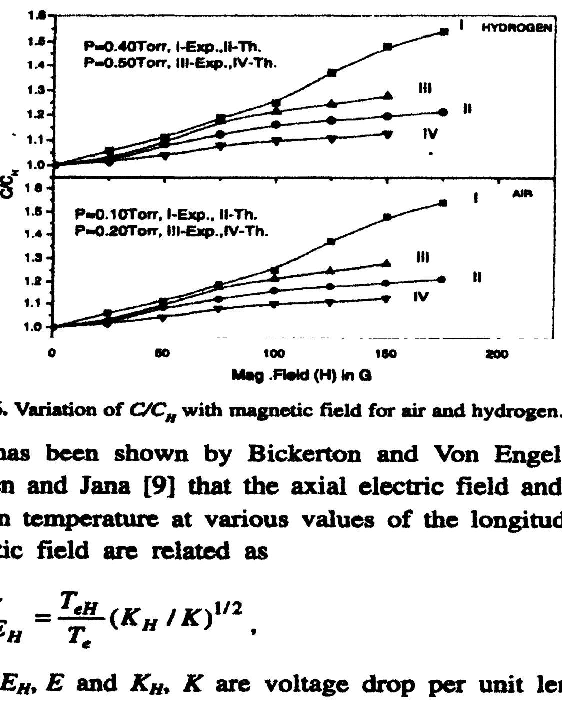


Figure 6. Variation of C/C_H with magnetic field for air and hydrogen.

It has been shown by Bickerton and Von Engel [8] and Sen and Jana [9] that the axial electric field and the electron temperature at various values of the longitudinal magnetic field are related as

$$E/E_H = \frac{T_{eH}}{T_e}(K_H / K)^{1/2}, \tag{5}$$

where E_H, E and K_H, K are voltage drop per unit length of the plasma and the fractions of energy lost by the electron due to elastic collision in presence and absence of magnetic field, respectively. They further showed that if $K_H = K$, then no new process results from the application of the magnetic field. As the values of E_H have been measured directly by our experiment, it is possible to calculate the ratio T_e/T_{eH} and the results are plotted graphically for air and hydrogen in Figure 7.

In order to evaluate theoretically the values of C and C_H and to compare it with the experimental results, it is inevitable to take some radial distribution functions for

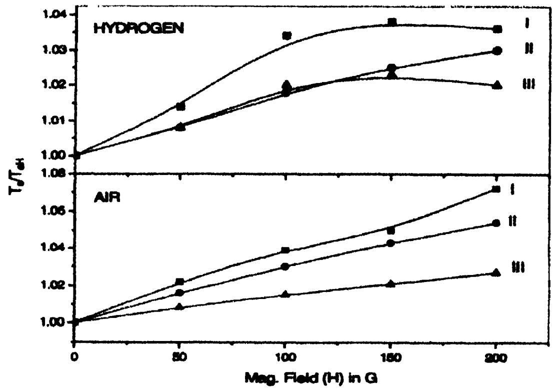


Figure 7. Variation of T_e/T_{eH} with magnetic field for air at pressure (P) I : 0.10 torr; II : 0.15 torr; III : 0.20 torr and for hydrogen at pressure (P) I : 0.40 torr; II : 0.50 torr; II : 0.60 torr.

the electron density for evaluation of the integral of eqs. (3 and 4). In the pressure between 0.10 and 10 torr where the diffusion theory holds, it has been shown by Schottky [13] that the loss of electrons and ions is entirely due to the diffusion. Further, it has been deduced by Sen and Jana [9] that

$$C/C_H = \left(\frac{v_i}{v_{iH}}\right)^{1/2} \frac{J_1(R_W / \Lambda_H)}{J_1(R_W / \Lambda)} \tag{6}$$

and

$$n_H/n = \frac{J_0\left\{\frac{r}{\Lambda}\left(\frac{v_{iH}}{v_i}\cdot\frac{E}{E_H}\right)^{1/2}\right\}}{J_0(r/\Lambda)}, \tag{7}$$

where J_0 and J_1 are the Bessel functions of zero order and first kind, v_i and v_{iH} are the frequency of ionisation in absence and in presence of magnetic field, respectively. In case of cylindrical tube, it can be shown that

$$\frac{1}{\Lambda} = \left[\left(\frac{\pi}{h}\right)^2 + \left(\frac{2.405}{R_W}\right)^2\right]^{1/2}$$

and $\dfrac{1}{\Lambda_H{}^2} = \dfrac{1}{\Lambda^2}\dfrac{v_{iH}}{v_i}\dfrac{E}{E_H}$,

where Λ is the diffusion length and Λ_H the effective diffusion length in presence of magnetic field, h is the distance between the electrodes and R_w is the radius of the discharge tube.

The variation of v_{iH} with magnetic field has been studied by Bickerton and Von Engel [8] in case of helium at low pressure and the expression given by Brown [12] is

$$\frac{\nu_{iH}}{\nu_i} = \frac{E}{E_H} \frac{eV_i}{K} \frac{E - E_h}{\alpha E_H}$$

where α is the proportionality between the electron temperature and the electric field for constant pressure. It is thus possible to calculate ν_{iH}/ν_i from different values of the magnetic field and pressure.

From eq. (6), it is also possible to calculate theoretically the ratio C/C_H. The variation of C/C_H with magnetic field is shown in Figure 6 in comparison with theory and experiment.

Figure 8 shows the change of frequency of the current pulses at fixed pressure 0.45 torr, with magnetic field. It is on the basis of the similar tendency towards an asymptotic of all three curves.

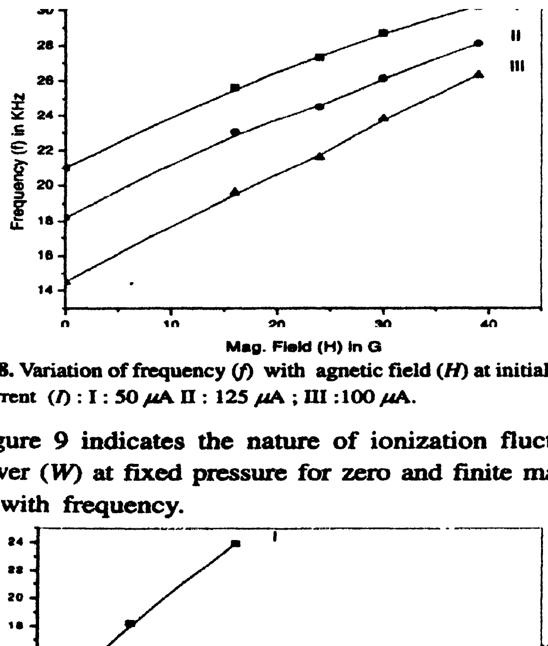


Figure 8. Variation of frequency (f) with agnetic field (H) at initial average tube current (I) : I : 50 μA II : 125 μA ; III :100 μA.

Figure 9 indicates the nature of ionization fluctuation of power (W) at fixed pressure for zero and finite magnetic field, with frequency.

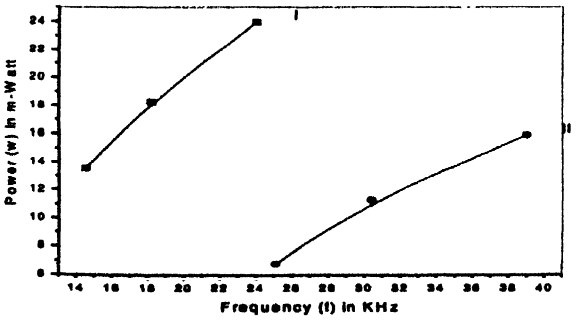


Figure 9. Variation of ionization fluctuation of power (W) with frequency (f) for hydrozoan 0.50 torr and mag. field (H); I : 0G; II 45G.

Figure 10 represents the ionization fluctuations of power (W) at constant magnetic field and average tube current, with pressure.

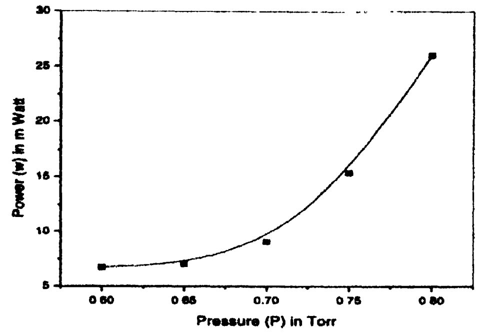


Figure 10. Variation of ionization fluctuation of power (W) with pressure (P) for hydrogen at average tube current (I) : 100 μA and magnetic field (H) : 45 G.

It is evident that though the theoretical results are not exactly equal to the experimental values, yet are close for low values of magnetic field used. This can be taken as a justification in favour of our assumption that the electron density profile is given by

$n = n_0 J_0(r/\Lambda)$ in absence of the magnetic field and by $n_H = n_0 J_0(r/\Lambda\{\nu_{iH} E/\nu_i E_H\}^{1/2})$ in presence of a longitudinal magnetic field.

It is also possible to justify our assumption with the help of electron density profile in presence and in absence of the magnetic field and to calculate theoretically n_H/n from eq. (7) and the results are represented in Figure 11.

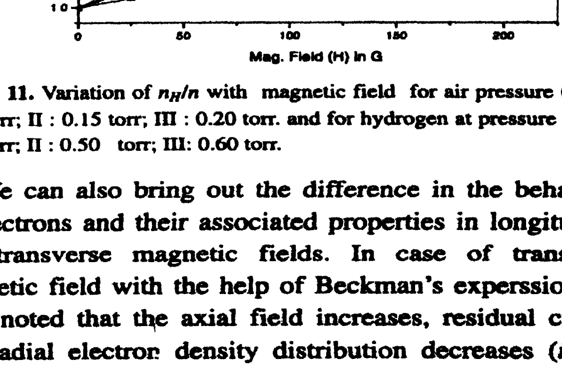


Figure 11. Variation of n_H/n with magnetic field for air pressure (P) : I : 0.10 torr; II : 0.15 torr; III : 0.20 torr. and for hydrogen at pressure (P) : I : 0.40 torr; II : 0.50 torr; III: 0.60 torr.

We can also bring out the difference in the behaviour of electrons and their associated properties in longitudinal and transverse magnetic fields. In case of transverse magnetic field with the help of Beckman's experssion, we have noted that the axial field increases, residual current and radial electron density distribution decreases (*i.e.* as reported in our previous paper [7]). The average tube current as well as residual current decreases depending on the pressure. On the other hand, for longitudinal magnetic field, the axial electric field, electron temperature decrease where as the average tube current, residual current and radial electron density and frequency of the current pulses increase and finally reach a constant value. In both the cases however, the radial distribution of electrons is governed by the normal Bessel function.

It is further pointed out that the results reported here have been made for a magnetic field up to 400 Gauss. The observed change in current, voltage, residual current and frequency of the current pulses are significant up to a field of 200 Gauss and beyond that they attend a constant value. The case of anomalous diffusion as noted by Lehnert [14] will depend not only upon the magnetic field H, but on the ratio of H/P, where P is the pressure. In our present investigation for the values of H/P using no evidence of anomalous diffusion has been observed perhaps because of the low discharge current used in the investigation. It can be seen that direct ionization is most efficient for small magnetic field.

The changes in oscillation parameters (*e.g.* frequency, band width, peak-peak voltage, rise time) of current pulses with magnetic field and pressure are presented.

4. Conclusions

It can be concluded from our work that the electron temperature, the radial distribution of electrons, the current voltage relation, residual current, oscillations parameters and other associated properties are different in case of a transverse magnetic field [7] than when the magnetic field is longitudinal.

The values of C/C_H is calculated theoretically and agrees with the experimental values for magnetic field. In this observations, it is noted that (a) the average tube current increases with the increase of longitudinal magnetic field so that the results can be explained and governed by normal Bessel function, and (b) the increase in frequency of the current pulses (ionisation fluctuations of power with magnetic field may be attributed to the fact that at relatively lower magnetic field, characteristic loss time for ions and electrons is higher. Also the observations of the ionization fluctuations of power for different pressures and at constant magnetic field indicated that the diffusion coefficient follows the inversely proportionality to the pressure.

A qualitative explanation has been provided for the variation of residual current with longitudinal magnetic field.

Rerefences

[1] M J Druyvestyn and F M Penning *Rev. Mod. Phys.* **12** 87 (1940)

[2] A L Ward *IEEE Trans.* **ED-10** 225 (1963)

[3] J S Townsend *Phil. Mag.* **25** 259 (1938)

[4] K G Emeleus *Int. J. Electronics* **39** 177 (1975)

[5] R S Nema and R K Shrivastava *J. Phys.* **D6** 1958 (1973)

[6] G Singh and R K Shrivastava *J. Phys.* **D18** 1125 (1985)

[7] D C Jana and S S Pradhan *Pramana-J.* **56** 107 (2001)

[8] R J Bickerton and A Von *Engel Proc. Phys. Soc.* **76** 468 (1956)

[9] S N Sen and D C Jana *J. Phys. Soc. Jpn.* **43** 1729 (1956)

[10] D C Jana and S S Pradhan *Pramana-J.* **60** 279 (2003)

[11] J J Thomson *Phil. Mag.* **11** 697 (1931)

[12] S C Brown *Basic Data in Plasma Physics* (MIT, Cambridge, Massachusates, USA : Technology Press) (1959)

[13] W Schottky *Phys. Zeitz* **25** 342 635 (1924)

[14] B Lehnert *Proc. 2nd V N Conference on Peaceful Use of Atomic Energy* (Geneva) 1958